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DYNAMIC DETERIORATION MODELING TO PREDICT THE FUTURE SEWER CONDUITS CONDITIONS

Kaddoura, Khalid[1,3] and Zayed, Tarek[2]
[1] Concordia University, Canada
[2] Hong Kong Polytechnic University
[3] kh_kaddo@encs.concordia.ca

Abstract: With no doubt, sewer networks serve an essential element of any infrastructure system. They are buried in nature; as a result, their conditions are rarely triggered unless collapse situations occur. Nevertheless, some efforts have been accomplished in designing specific inspection cameras and sensors to help assessing sewer pipelines considering several sewer protocols. These protocols supply condition grades that suggest the overall conditions of the assets. Therefore, decision-makers can monitor the pipelines' states throughout their service lives. However, these conclusions encourage reactive maintenance, which results in significant costs and time when compared to proactive strategies. One method that could promote deploying the latter strategy is the deterioration modeling. These models are specially designed to predict the future conditions of any asset. Therefore, it assists practitioners in scheduling for inspection and deciding on the maintenance, rehabilitation or replacement (MRR) actions. As a result, the objective of this research is to design a dynamic deterioration model by employing the Weibull distribution analysis. The methodology shall propose three different deterioration curves: i) the ideal deterioration curve, which describes the ideal states of the pipelines' deterioration considering a specific service life; ii) the updated deterioration curve (UDC), which models the deterioration of the pipeline considering the condition after inspection; iii) the predicted deterioration curve (PDC), which models the deterioration of the pipeline after rehabilitation actions. This study is expected to provide informative conclusions for decision-makers when it comes to planning for inspection or MRR decisions for sewer pipelines.

1 Introduction

Sewer networks are recognized as significant part of the public health (Duchesne et al. 2013; Kaddoura et al. 2017) as they transfer sewage medium to treatment plants or special disposal areas. In fact, they form one of the most capital intensive infrastructure in North America (Wirahadikusumah et al. 2001). Considerable amount of budgets shall be reserved to enhance, repair, maintain or replace constructed sewer assets as sooner or later, their service life will be reached (Wirahadikusumah et al. 2001). Sewer assets are subject to deterioration due to ageing; therefore, it is significant to inspect their conditions regularly to make optimum decisions and avoid any disruption. Nevertheless, the information provided by the inspection supplies general and current state of the asset in which reactive actions are followed (Baik et al. 2006) relying on a "fix it if and when it fails" technique (Fenner 2000). Moreover, such a practice results in comprehensive public and safety problems. Besides, it incurs significant amount of money ranging from two to ten times more than proactive strategies. Thus, predicting the future condition of infrastructure assets is crucial to plan for proactive strategies to lessen the budgets allocated for maintenance and rehabilitation (M&R). Number of researches has been designed to model the deterioration of infrastructure assets. As per Morcous et al. (2002a), these models are composed of three groups: polynomial-type models, artificial intelligence models and stochastic or probabilistic models.

Polynomial-type models utilize continuous functions to understand the effect of different factors (explanatory variables) in the system on the condition of the asset. For example, Chughtai and Zayed (2008) proposed a polynomial regression model to predict the condition of sewer pipelines. The authors classified different factors and subfactors into structural and operational groups. Subsequently, data from a municipality was used to construct the regression models. The structural and operational grades predictions for different pipeline materials were proposed in which were used to plot the deterioration curves. In a similar work, Bakry et al. (2016a) developed a prediction model for cured-in-place pipelines (CIPP) rehabilitated sewers and another model to predict the condition of chemically grouting rehabilitated pipelines and manholes (Bakry et al. 2016b). The authors relied on a dataset brought from a local municipality to implement and validate their models. Later, the models were used to establish deterioration curves to understand future states of the assets. One significant limitation of polynomial-type technique is that condition ratings indicate a relative ordering with no or minimal meaning assigned to the distance between the conditions ratings (Scheidegger et al. 2011). Consequently, the continuous functions are inappropriate for representing discrete ordinal measures (Scheidegger et al. 2011).

Other researchers, however, employed artificial intelligence models, which are information driven techniques. Usually, the outputs of the model are supplied after learning from available input data. Morcous et al. (2002b) proposed a case-based reasoning to model infrastructure deterioration assuming that the performance of an infrastructure asset can be predicted by the recorded performance of other assets that share similar attributes. After identifying six requirements to design their model, the developed prototype was able to predict the future condition of the bridge decks. In a work related to Artificial Neural Network (ANN), Najafi and Kulandaivel (2005) developed a model to predict the condition of sewer pipelines based on historic condition assessment data. The authors used multiple variables for the ANN model such as the length, size, material type, age of sewer, depth of cover, slope and type of sewer. It is true that artificial intelligence techniques can handle condition ratings and non-linear deterioration behavior, their main limitation is that they require considerable amount of data to establish a robust and reliable model (Scheidegger et al. 2011).

Furthermore, infrastructure deterioration were modeled using stochastic (probabilistic) techniques such as Markov chains technique. For example, Wirahadikusumah et al. (2001) presented a Markov chain-based deterioration model for large buried combined sewers. The authors utilized an exponential model in the regression analysis to relate between the overall structural grade and the sewer age. Based on the authors' premise, the condition of sewer did not decrease by more than one state in one year transition. The transition probabilities among five different identified states were predicated using the nonlinear optimization-based approach. Distinct deterioration models were plotted considering different combinations of factors (material, groundwater level, backfill material and depth of cover). Additionally, Kleiner (2001) proposed another Markov chain-based deterioration models for water and sewer systems. The author assumed a single state transition among the condition states considered. Besides, the transition time was fitted as a random variable using Weibull distribution analysis. The author disregarded significant factors that could expedite the asset's deterioration and relied only on the age of the asset. Also, Micevski et al. (2002) developed a Markov chain- deterioration model for water pipelines. The authors assumed multiple state transitions among the four identified states, in which the Metropolis-Hastings algorithm was used to estimate the transition probabilities. The authors claimed different deterioration rates for different pipeline categories: pipeline diameter, soil type, pipeline material and adjacency to coastline.

Baik et al. (2006) proposed a Markov chain-based deterioration model to estimate the future condition of wastewater systems. The authors assumed five different states to construct the transition probability matrix. The transition probability matrix was estimated using the concepts of an ordered probit model along with an incremental model. The variables used for the ordered probit model were the length of the pipeline, the diameter size, the type of pipeline material, the age and the slope of the pipeline. In addition, the authors applied the nonlinear optimization technique-based approach to estimate the transition probabilities before concluding that the ordered probit model approach was statistically and theoretically more robust. Nevertheless, the authors reported several limitation to their findings. Despite the comprehensive and extensive efforts accomplished by many researchers who applied Markov chain models, the technique's main limitation is the accuracy and the ability of estimating the transition probability matrix.

In asset management, decision-makers are constrained by limited access to historical database and are continuously attracted to noncomplex techniques to save time and efforts. Based on the literature review, the utilized techniques, are complex and static in nature. Hence, this research proposes a dynamic deterioration modeling that is based on Weibull analysis. This method does not require significant historical data to construct the deterioration of the pipelines. In fact, it requires one condition input and can be updated whenever new inspections are conducted. As a result, municipal engineers are well aware of the future condition of each pipeline to make proactive M&R plans and actions.

2 Research Methodology

This paper utilizes the Weibull distribution technique to construct the deterioration curves for sewer assets. This technique proved its applicability and fast implementation as it does not require the condition history of the asset as many municipalities lack the records of the sewer networks. As a result, it facilities plotting the deterioration distribution for any asset by decision makers using one data point. As per Figure 1, there are three main curves the ideal deterioration curve (IDC), the updated deterioration curve (UDC) and the predicted deterioration curve (PDC). The first curve to be constructed is the IDC which relies on parameters such as the expected sewer pipelines service life. Therefore, the constructed curve shall represent the ideal deterioration of a pipeline until it reaches the critical condition. However, the UDC is established by feeding the condition information and therefore, the UDC can either underperform or outperform the IDC. Nevertheless, the PDC is drawn to represent the M&R improvements once applied such as minor and major M&R or replacements.

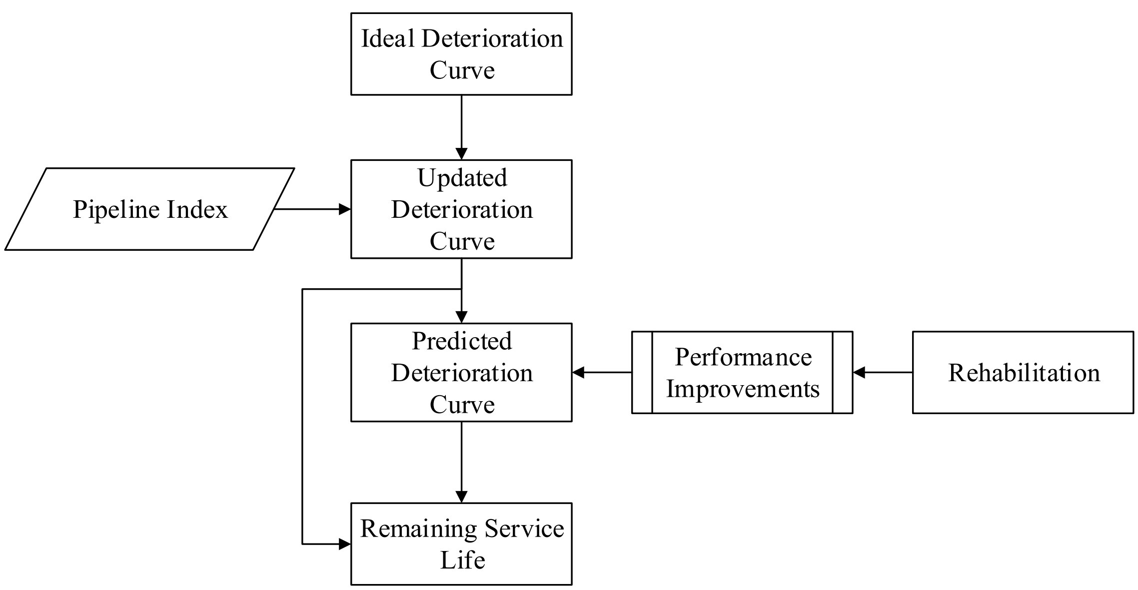

Figure 1: Asset deterioration curve formulation process

2.1 Ideal Deterioration Curve (IDC)

The IDC is constructed to overcome the difficulty in estimating the Weibull distribution factors. Obtaining a Weibull reliability shape deterioration function that considers the history of reports for each asset is difficult.

However, this research overcomes this obstacle by plotting the IDC considering certain conditions. The reliability function starts at the maximum performance level and stays constant for a certain period of time, where the slope is equal to zero. In practice, once the asset is constructed, the asset functions properly and in excellent condition before the condition starts to deteriorate. After sometime, the condition starts to decrease and so its reliability, which forms a negative slope. The actual scenario of the asset's deterioration can be modelled using the Weibull distribution analysis. The Weibull probability distribution function is defined as the following:

[1] $f(t) = \frac{\delta}{\tau}(\frac{t-\alpha}{\tau})^{\delta-1} * e^{-(\frac{t-\alpha}{\tau})^{\delta}}$ for $t > \alpha$

where α is the location factor, τ is the scale factor, δ is the shape factor and *t* is the time.

Therefore, the cumulative Weibull distribution function (cdf) is described as in Equation 2

[2] $F(t) = 1 - e^{-(\frac{t-\alpha}{\tau})^{\delta}}$

Thus, the reliability function can be described according to Equation 3:

[3] $R(t) = F(t) = 1 - e^{-(\frac{t-\alpha}{\tau})^{\delta}}$

Hence, the IDC can be described according to Equation 4, which shares a similar shape of that in the previous equation.

[4] $IDC(t) = \alpha * e^{-(\frac{t}{\tau})^{\delta}}$

Certain conditions are applied to construct the IDC curve which therefore has specific characteristics:

- At the time zero or once the asset is constructed and put for use, the slope of the curve is zero as per the following:

  $$\frac{\partial(P_I^{IDC})}{\partial t} = P_I^{IDC'}(t) = 0$$

- The ideal Service life of sewer pipelines and manholes is 75 years
- For a scale 1-5, The lowest performance is 0.2 (1/5)
- At *t* = 0 , the reliability of the asset shall be 1.00 (excellent condition); as a result,

  [5] $1 = \alpha * e^{-(0/\tau)^{\delta}} = \alpha$

  Therefore, $\alpha = 1.00$

- At t = 75 years, the reliability of the asset is equal to the lowest performance which is 0.2.

  Therefore,

  $0.20 = 1 * e^{-(75/\tau)^{\delta}}$, then
  [6] $\tau = \frac{75}{\sqrt[\delta]{-\ln(0.2)}}$
  The shape factor shall be greater than 1. The optimum value of δ is equal to 3 as other integers do not supply a desired deterioration curve. Considering δ = 3,

$\tau = \frac{75}{\sqrt[3]{-\ln(0.2)}}$ τ = 64.00 years

As a result, the Condition Index for Pipelines at time t (CI_P) is described in Equation 7:

[7] $CI\_P\_IDC\ (t) = 1 * e^{-(\frac{t}{64.00})^3}$

Using Equation 7, Figure 2 is plotted, which displays the ideal deterioration of any pipeline subject to the assumptions stated earlier.

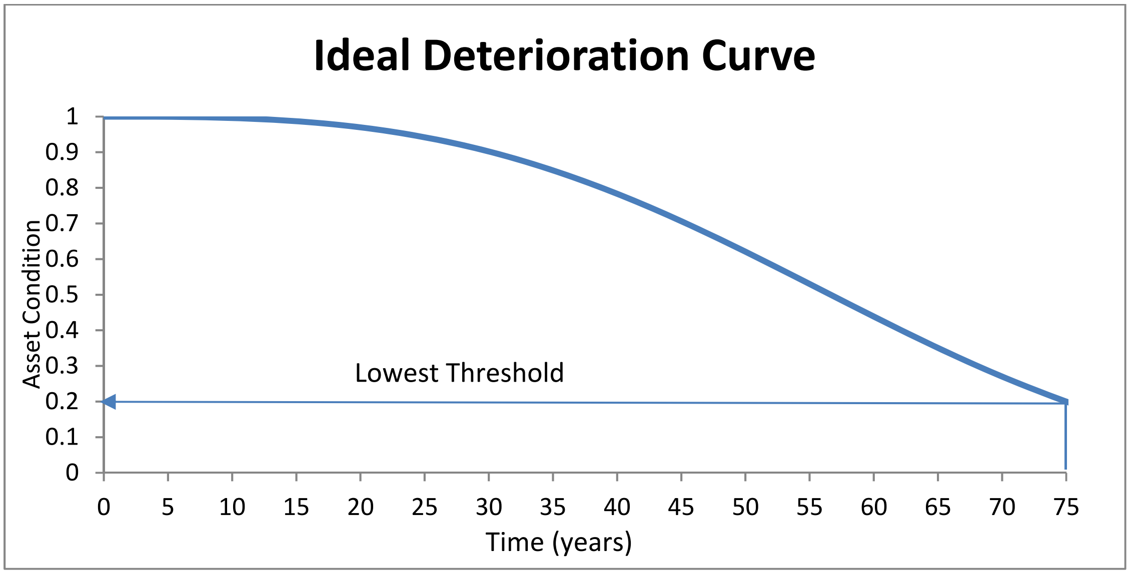

Figure 2: IDC

2.2 Updated Deterioration Curve (UDC)

The IDC is constructed to understand the ideal deterioration of the assets involved considering certain conditions as illustrated earlier. However, not all assets inspected share similar deterioration curves and therefore, the deterioration curve shall be updated; herein is called the UDC. The distribution is modified considering an input value (condition), which is used to plot the curve. Therefore, an updated service life is concluded.

The UDC is constructed after attaining certain conditions, which are the only inputs for UDC, as follows:

- Similar to the UDC, at *t* = 0, the condition will be at maximum which is 1.00

  [8] $1.00 = \alpha * e^{-(0/\tau)^{\delta}} = \alpha$

- At *t* = 0, the slope is zero as per the following

  $$\frac{\partial(P_I{}^{UDC})}{\partial t} = P_I{}^{UDC\prime}\ (t) = 0$$

- At any time (t_i), the condition of the asset is described as follows

  [9] $CI_i = 1 * e^{-(\frac{t_i}{\tau})^{\delta}}$

  and therefore,

[10] $\tau = \frac{t_i}{\sqrt[\delta]{-\ln(CI_i)}}$

Where t_i is the inspection at time *(t)* and CI_i is the condition index at time t_i. Similarly, $\delta = 3$ as the other integers do not provide the desired deterioration curve. By substituting τ with the shape factor value, the updated *CI_P.*

[11] $CI\_P\_UDC(t) = 1 * e^{\ln(CI\_P_i)(\frac{t}{t_i})^3}$

Where *CI_P_UDC* is the updated condition index of the pipeline at any time t_i, CI_P_i is the condition indexes at any time t_i of the pipeline. Considering the aforementioned equations, the UDC can be plotted for any asset. Figure 3 illustrates the UDC and the IDC of a pipeline. In this example, the asset is underperforming as the curve is below the IDC and hence, it will reach to the critical condition before the assumed 75 years.

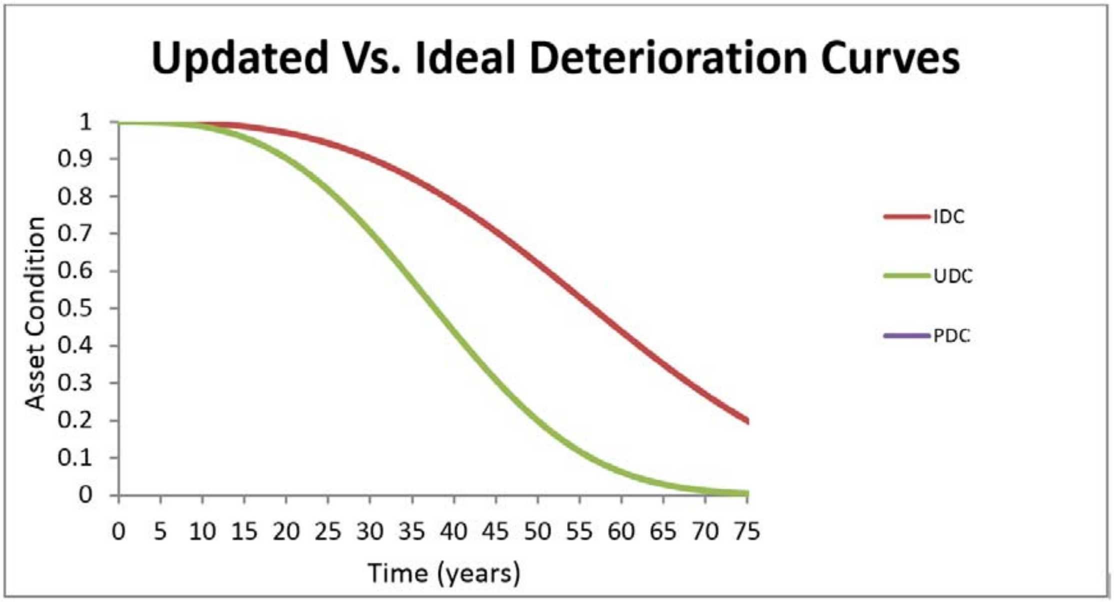

Figure 3: UDC vs. IDC

2.3 Predicted Deterioration Curve (PDC)

The last deterioration curve constructed is the PDC. Since pipelines are subject to deterioration over time, municipalities are required to allocate budgets for maintenance and rehabilitation at a specific time *(t_m).* These actions, once implemented, shall enhance the condition and the performance of the asset. Therefore, before any rehabilitation action, the deterioration of the asset shall follow the curve of the IDC in case of an ideal situation or the UDC in case of an updated curve. Once a rehabilitation action is accomplished, the enhancement is immediately considered in the PDC. Therefore, the performance is expected to increase and so the service life of the asset.

Similar to the UDC evaluation, the t_i is substituted by t_m and the CI_i by the CI_m. Therefore, the PDC of the pipelines before any M&R actions is defined as in equation 12.

[12] $CI\_P\_PDC(t) = 1 * e^{\ln(CI\_P_m)(\frac{t}{t_m})^3}$

where t_m is the time of M&R action, *CI_P_PDC (t)* is the condition of the pipeline before M&R at time $t_;$ CI_P_m is the condition of the pipeline directly before M&R.

Since the condition of the asset is expected to improve at (t_m + 1) after M&R actions; therefore, the improved condition is described by Equation 13

$CI\_P_M = CI\_P_m + \Delta M\_P$ [13]

where CI_P_M is the pipeline condition immediately after M&R actions; ∆M_P is the pipeline condition improvement. The improvements are user defined values and can differ from one intervention plan to another. For example, replacing the whole pipeline can return the condition of the pipeline to 1 “Excellent.

Therefore, the PDC of the pipeline is according to Equation 14:

$$CI\_P\_PDC\ (t) = CI\_P_M * e^{\ln(CI\_P_{M_i}) * (\frac{t-t_m+1}{t_i})^3} \qquad [14]$$

Subsequently, the IDC, UDC and PDC can be plotted and represented as follows. As per Figure 5, once the M&R actions are conducted, a spike in the asset condition is observed. In Figure 5, the improvement enhanced the condition to 3.5 in a scale of 1-5.

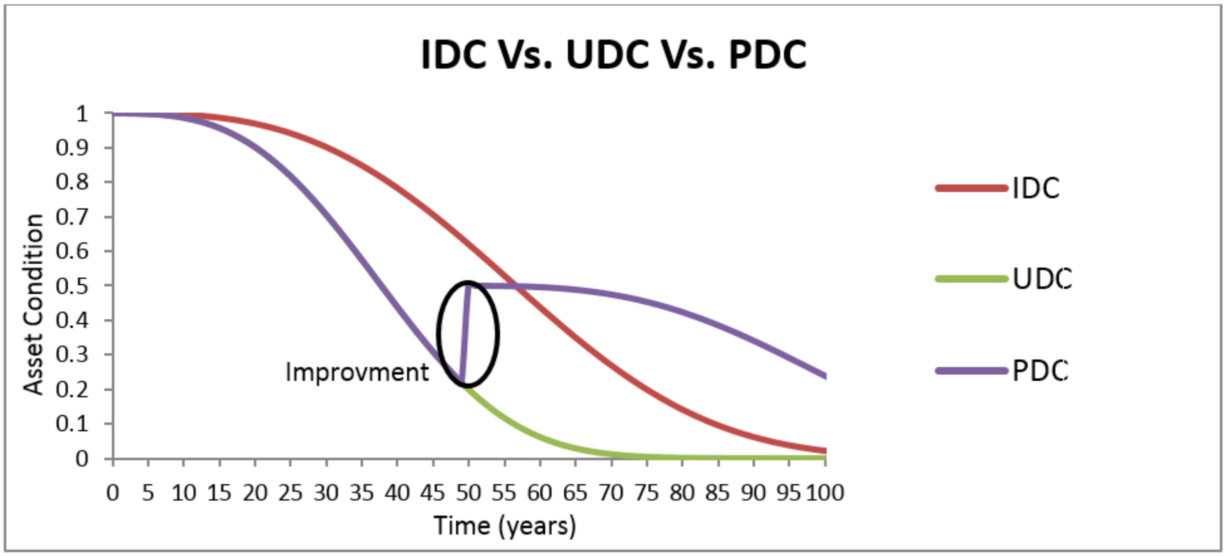

Figure 5: IDC vs. UDC vs. PDC

3 Model Implementation

This model has been implemented on one sewer pipeline that is located in Royal Gardens area, Edmonton. The IDC model is the baseline model that represents the ideal condition of sewer pipeline's deterioration. If a pipeline is performing below the IDC, the pipeline will collapse before the considered service-life and vice-versa. However, the UDC model describes the deterioration of the asset based on the input data that is extracted from inspection reports. The condition index ranged between 1 and 5, where 1 is an excellent condition while 5 is a critical condition. Based on the input data, the reliability of the asset is transferred to 0.2 to 1, where 1 represents the excellent condition and 0.2 describes the critical condition of the pipeline. According to the input data, the deterioration of the pipeline is shown in Figure 6. Based on the the figure, the pipeline is performing better than the ideal condition and the pipeline is expected to reach to condition five at an age of 109 (year 2074). In case decision-makers decide to rehabilitate or replace the pipeline, the condition shall enhance according to PDC curve.

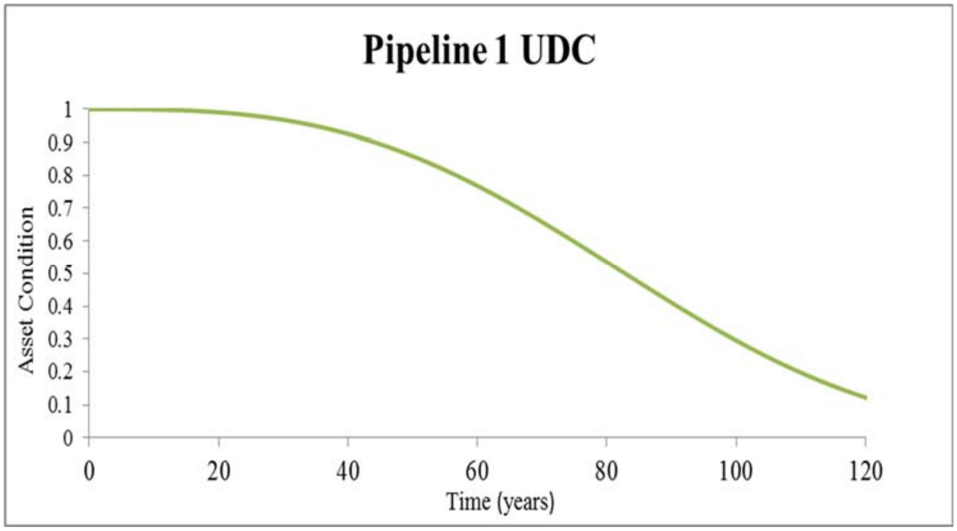

Figure 6: Pipeline 1 UDC

4 Conclusions

The main objective of this research was to develop dynamic deterioration curves for sewer conduits. The application of the proposed Weibull analysis methodology provided three types of curves: the ideal deterioration of the assets, the updated deterioration based on the current condition and the deterioration beyond the rehabilitation actions. Pipelines that perform below the IDC are expected to collapse before the considered service-life and vice versa. This methodology has been implemented on a pipeline that is located in Edmonton, Canada. The deterioration curve of the pipeline has been modeled based on the inspection report. The effectiveness of this model can be further proved by comparing it with existing models. However, actual data pertinent to deterioration of assets were scarce. Despite the aforementioned fact, this model shall aid decision-makers to identify pipelines that will collapse before their expected service-life without relying on huge historical data. Therefore, reactive interventions are lessened, while proactive interventions are conducted based on a pre-planned budget allocation.

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